Hydrologic Hazards

Best Practices in Dam and Levee Safety Risk Analysis

Part B - Hazards and Loading

Chapter B-1

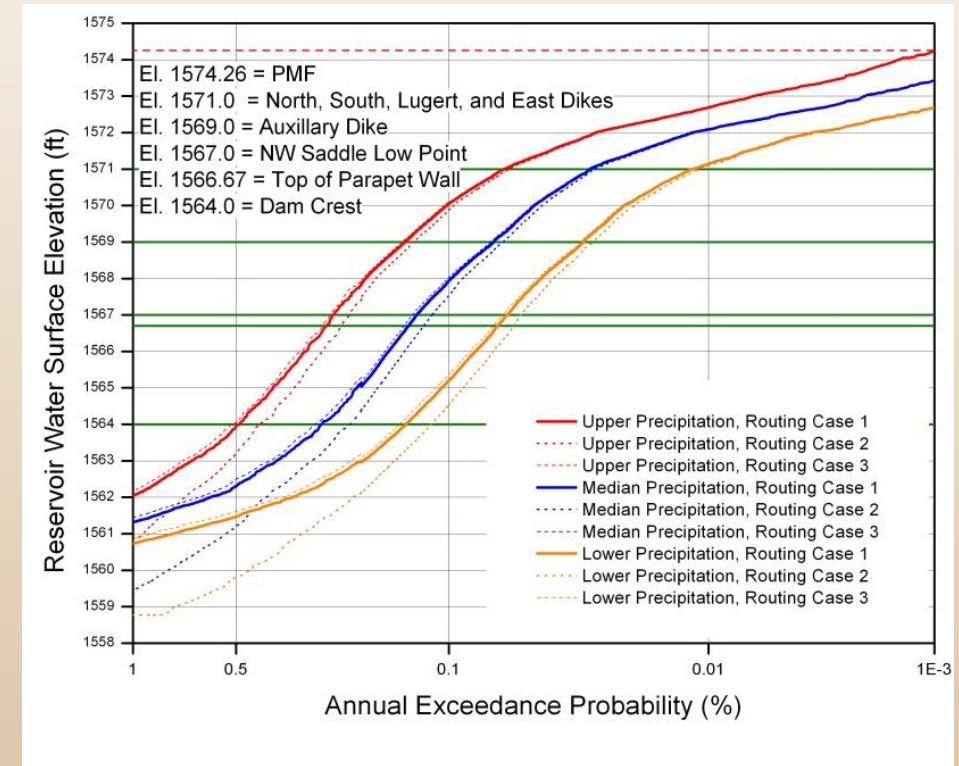July 2018

Objectives

- Understand the methods used to characterize hydrologic hazards

- Understand how hydrologic hazards are used to estimate risks

Key Concepts – Hydrologic Hazards

- Variables, magnitudes, and ranges of interest for risk estimate
  - Stage, discharge, volume, velocity, others
  - Peak, timing, duration
- Entire distribution shape matters
- Load partitioning important to develop a proper event tree
- Integration of hazard with failure modes and consequences
- Deterministic floods not easily mapped to hazard curves
- Quantify and understand uncertainty

Outline

- Why are hydrologic hazards important?
- Some Hydrologic-Related Potential Failure Modes
- What's a Hydrologic Hazard Curve?
- Hydrologic Hazards - Current Guidance
- Hydrologic Hazard Curve Estimation – Key Principles and Methods
- Hydrologic Hazards and use in Risk Analysis

Why Flood Hazards are Important

Cause of Dam Failures: 1975-2001
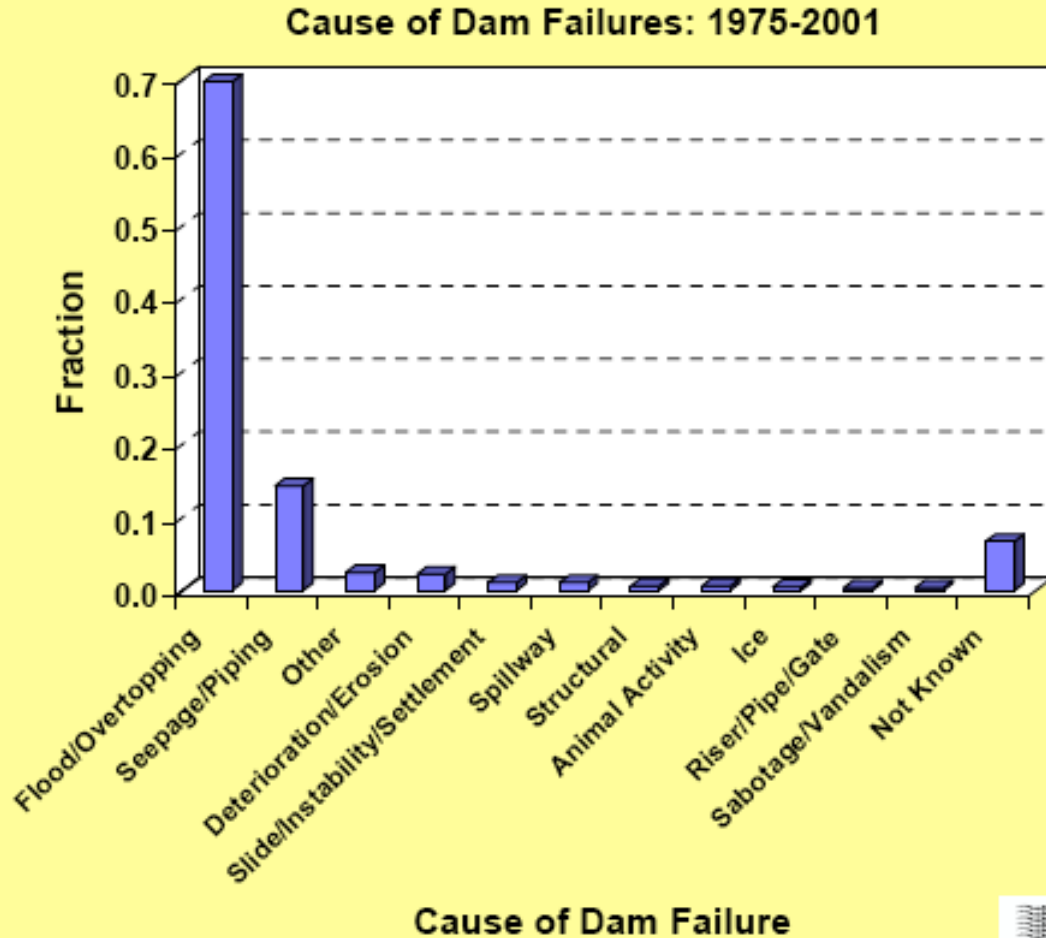
Dam	Year	Fatalities
South Fork, PA	1889	2,209
Walnut Grove, AZ	1890	100
Buffalo Creek, WV	1905	125
Swift Dam, MT	1964	19
Canyon Lake, SD	1972	237
Laurel Run, PA	1977	40
Kelly Barnes, GA	1977	39
Rainbow Lake, MI	1986	3
Callaway, TX	2002	2
Ka Loko, HI	2006	7

Why Flood Hazards are Important

Levee Overtopping
Mississippi River
July 1993

Floodway Operation
Mississippi River
May 2011

Dam Overtopping
Iowa
July 2010

Refer to Case Histories for More Details and More Examples

Why are Flood Hazards Important

Annualized Failure Probability

$$f = P_l * P_{r|l}$$

Risk: Annualized Life Loss

$$Risk = P_l * P_{r|l} * C$$

P_l = Probability of Load – **Hydrologic Hazard Curve**

$P_{r|l}$ = Probability of Adverse Response Given Load
C = Consequences (or Loss of Life, N)

Potential Failure Modes

- Almost all of them
  - No water = No failure mode

- Overtopping of Dams and Levees
  - erosion of downstream toe, foundation, or dam crest

- High Reservoir Levels or River Stages
  - Internal erosion, instability, and many others

- Spillway and Stilling Basin
  - erosion, cavitation, wall overtopping

- Misoperation or malfunction
  - Gate electrical/mechanical, pump stations, closures

What is a Hydrologic Hazard Curve?

- A probability distribution
  - Survival function or Exceedance curve
- Annual probability that stage will be exceeded (>)
  - Same applies for discharge, volume, velocity, etc
- Risk estimates need the full range of values, with uncertainty
- Range that drives risk will depend on PFMs and consequences
  - *< 1 in 10,000 (dams)*
  - *< 1 in 1,000 (levees)*
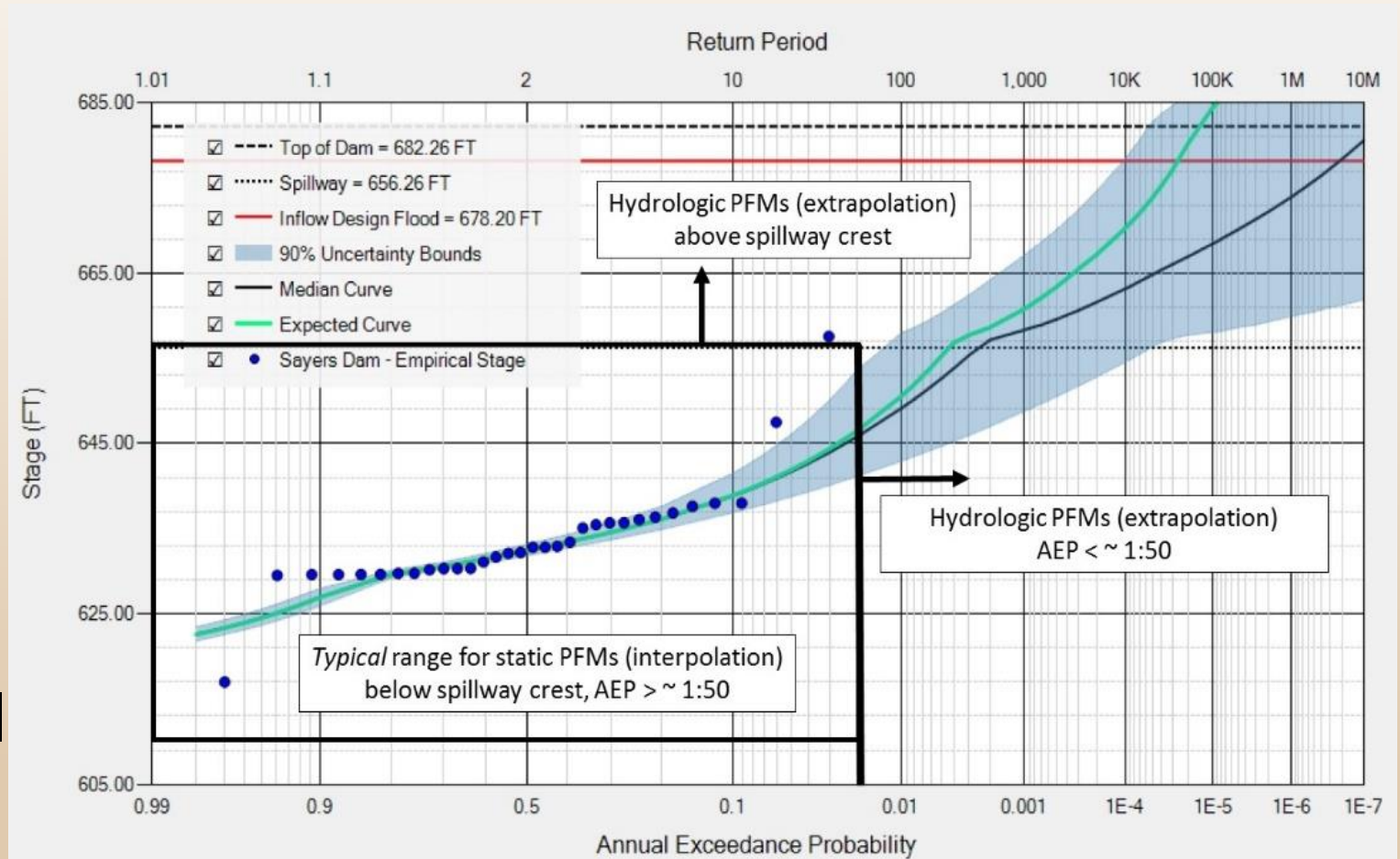
Hydrologic Hazard: Discharge and Volume

Leverage all available information
- Gage records
- Historic flood records
- Paleoflood studies
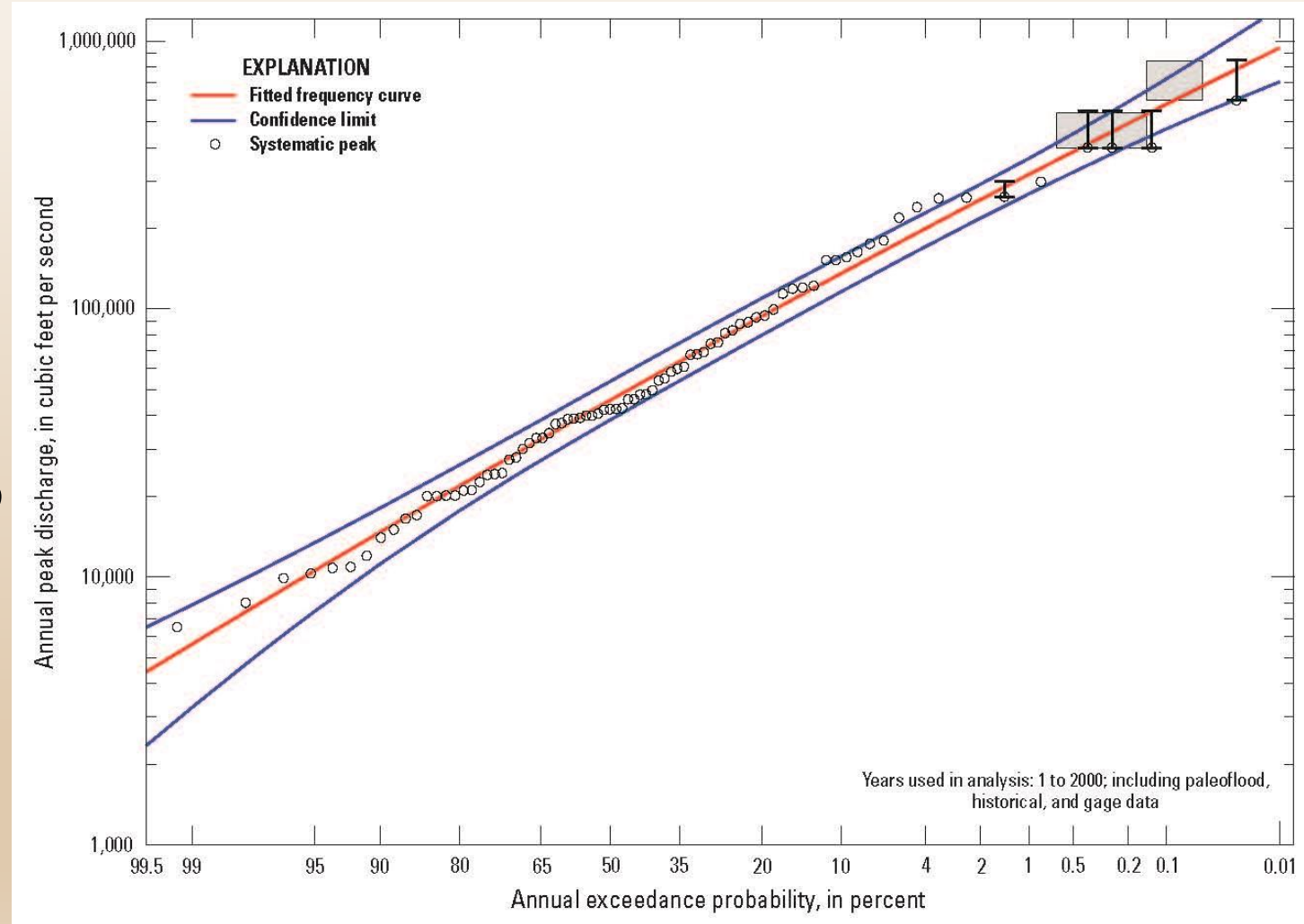
Use current methods
- Bulletin 17C

Do not anchor
- Do use an assigned AEP for the PMF to define the curve
- Ok to report the AEP for the PMF discharge or volume from the curve

Quantify uncertainty
- Typically large due to extrapolation

Identify key parameter
- Peak
- Volume (for the critical duration)

EXPLANATION
— Fitted frequency curve
— Confidence limit
○ Systematic peak

Years used in analysis: 1 to 2000; including paleoflood, historical, and gage data

Annual peak discharge, in cubic feet per second
Annual exceedance probability, in percent

[Bulletin 17C Appendix 10 Example](#)

Hydrologic Hazard: Reservoir Pool or River Stage

Understand how physical characteristics influence the shape of the curve

- $I - O = dS/dt$
- Downstream controls
- Gate operations
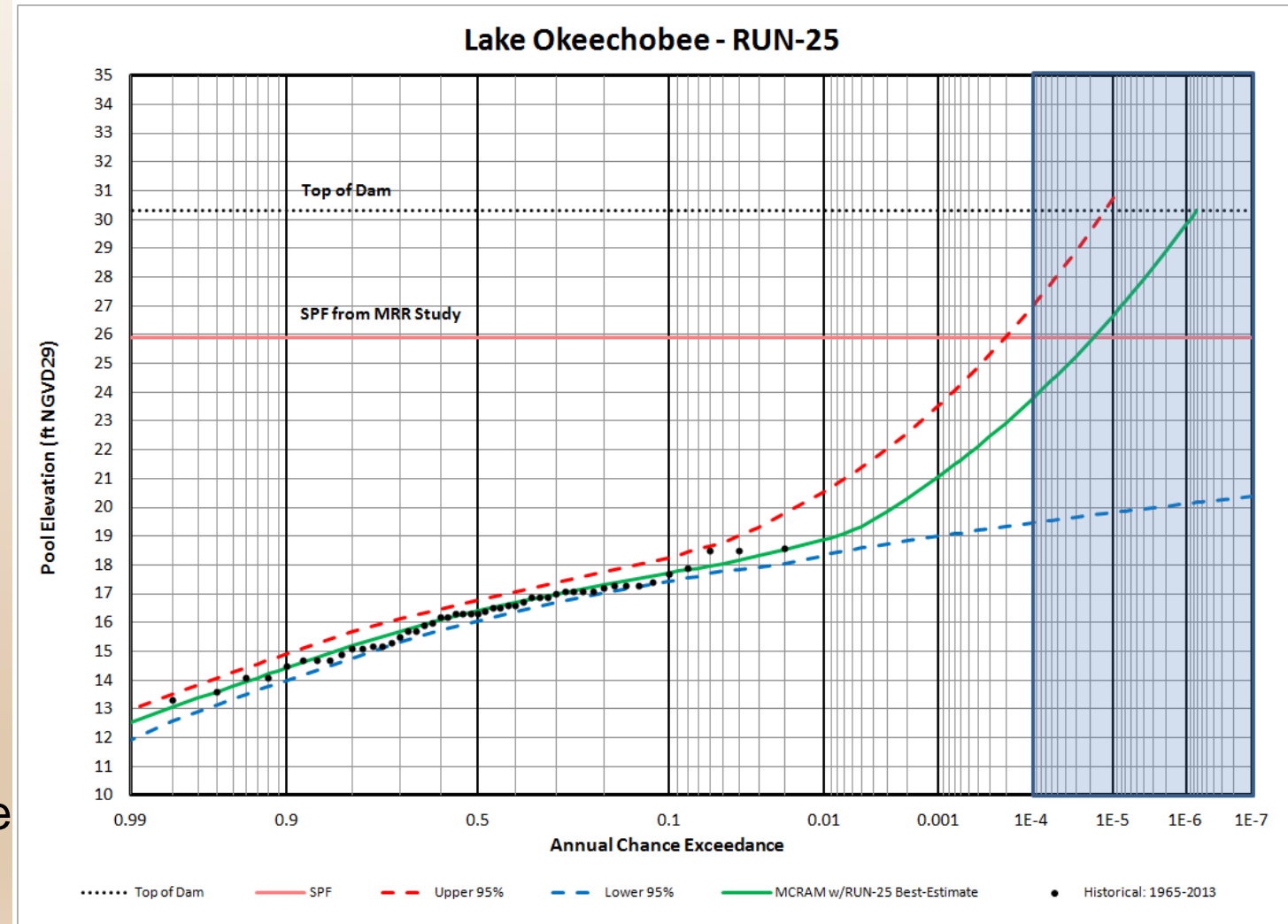- Spillway crest
- Overtopping flows
- Storage

Leverage available data

- Observed stages
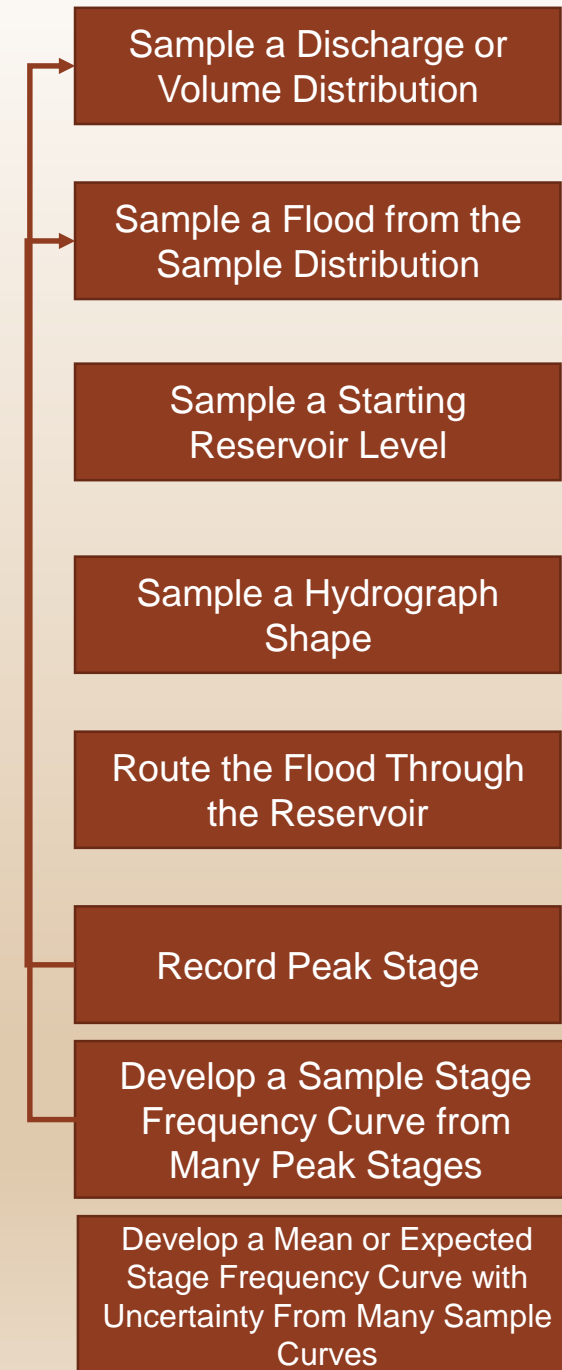- Reconstruct historic events

No anchoring

- Do not assign an AEP to the PMF to define the curve
- Ok to report the AEP of the PMF stage from the curve

Uncertainty

Lake Okeechobee - RUN-25

# Stochastic Modeling

- Monte Carlo Simulation
- Used to combine uncertainties
  - Precipitation
  - Discharge or volume
  - Starting reservoir or river level
  - Hydrograph shape
  - Many others possible
- No single point estimates
- Some items are typically reserved for the event tree based on needs and preference
  - For example, gate reliability and debris blockage
  - Develop separate hazard curves for several assumed gate and debris scenarios
  - Address probabilities for the gates and debris scenarios in an event tree
 - Easier to attribute the contribution of gates and debris to project risk

Sample a Discharge or Volume Distribution

Sample a Flood from the Sample Distribution

Sample a Starting Reservoir Level

Sample a Hydrograph Shape

Route the Flood Through the Reservoir

Record Peak Stage

Develop a Sample Stage Frequency Curve from Many Peak Stages

Develop a Mean or Expected Stage Frequency Curve with Uncertainty From Many Sample Curves

Current Guidance on Hydrologic Hazard Estimation

Reclamation, USACE and FERC implementing and using similar methods for hydrologic hazards; some technical details on methods in these reports
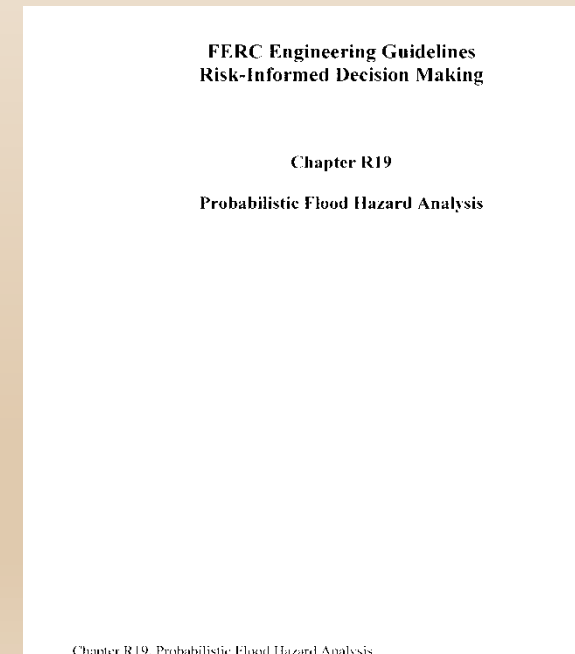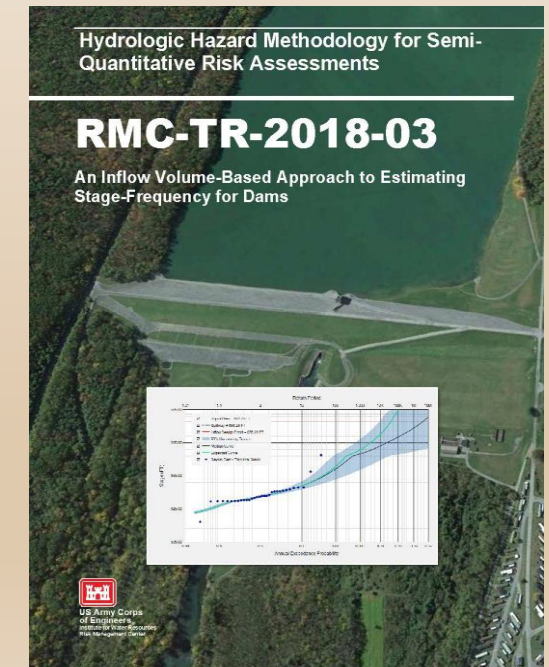
Reclamation, 2006
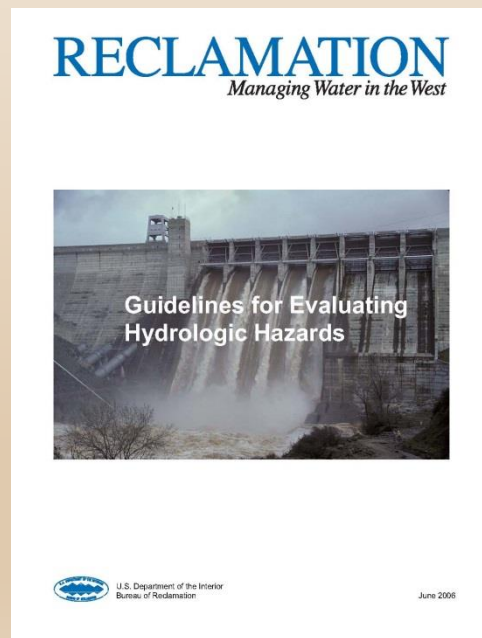
USACE, 2015;
under development/revision
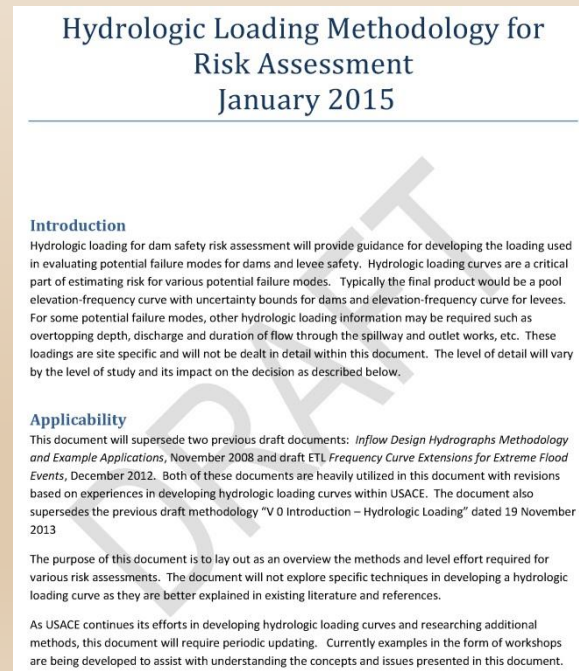
FERC, 2014
draft for public

USACE, 2018;
SQRA

See Chapter References for links to documents

Hydrologic Hazard Guiding Principles

- No Single Approach Describes Flood Hazards Over the Range of AEPs Needed – *Multiple Methods: combine flow frequency curves and rainfall-runoff curves*

- Greatest Gains From Incorporating Regional Precipitation, Streamflow, Paleoflood Data – *Lots of Data*

- Honestly Represent Uncertainty – *Explicitly Quantify Uncertainty*

- Temporal Information: expand data in time
- Spatial Information: expand data in space
- Causal Information: utilize hydrological understanding of flood-producing processes

- Do Not Assign an AEP to the PMF

A Framework
For Characterizing
Extreme Floods for
Dam Safety Risk Assessment

Prepared by
Utah State University
and
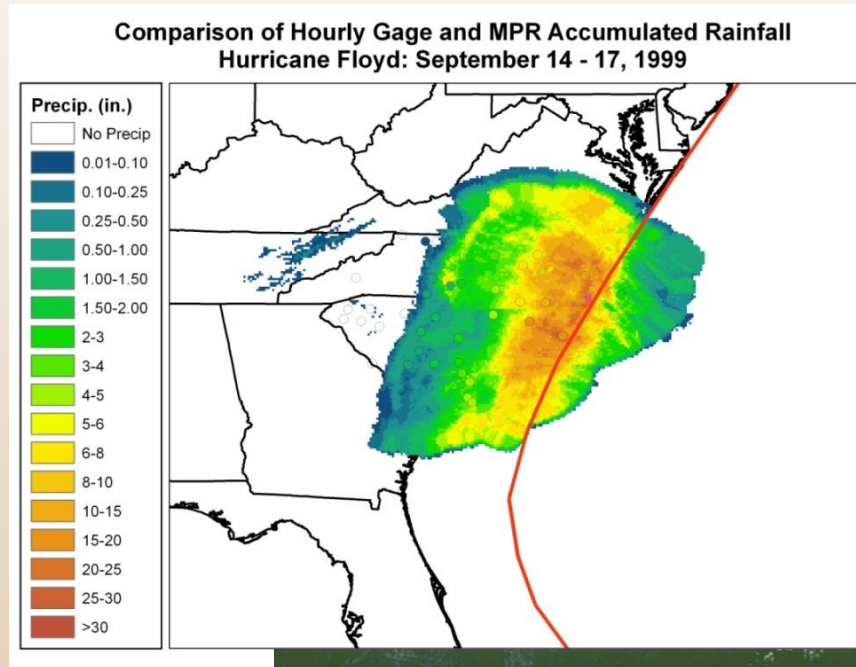United States Department of the Interior
Bureau of Reclamation

November 1999

Expertise

Meteorology **Hydrology** **Statistics** **Paleoflood**

Interdisciplinary Skills Needed

Storm Types and Processes

Comparison of Hourly Gage and MPR Accumulated Rainfall
Hurricane Floyd: September 14 - 17, 1999

Precip. (in.)

No Precip
0.01-0.10
0.10-0.25
0.25-0.50
0.50-1.00
1.00-1.50
1.50-2.00
2-3
3-4
4-5
5-6
6-8
8-10
10-15
15-20
20-25
25-30
>30

Storm Brook, a small tributary of Connecticut River, at Suffield, Conn., the morning of August 19, 1955. Photograph by Roger C. Loomis.

Examples
Hurricanes and TCs – Eastern US
Convective Thunderstorms - Flash floods

Credible Extrapolation
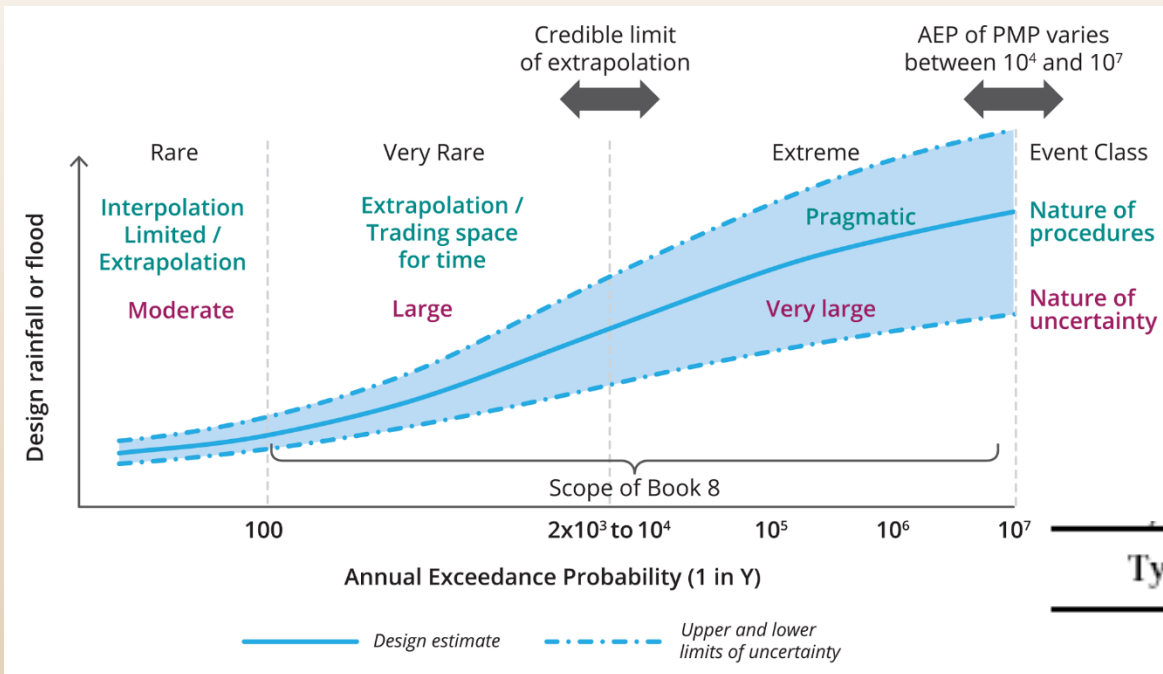
USBR - USU (1999), Swain et al. (2006)

Also in: Australian Rainfall & Runoff (2016) Book 8 Estimation of Very Rare to Extreme Floods by Nathan and Weinmann
http://arr.ga.gov.au/

Type of data used for flood frequency analysis	Range of credible extrapolation for Annual Exceedance Probability	
	Typical	Optimal
At-site streamflow data	1 in 100	1 in 200
Regional streamflow data	1 in 500	1 in 1,000
At-site streamflow and at-site paleoflood data	1 in 4,000	1 in 10,000
Regional precipitation data	1 in 2,000	1 in 10,000
Regional streamflow and regional paleoflood data	1 in 15,000	1 in 40,000
Combinations of regional data sets and extrapolation	1 in 40,000	1 in 100,000

Data Sources

- Extreme Rainfall Data
  - NCDC gages
  - Depth-Area Duration storm catalog from USACE, Reclamation, NWS
  - MPE and MPR gridded precip (NWS)
- Extreme Flood Data
  - USGS stream gages: peaks, hydrographs
  - Historical information (photos, eye witness accounts, newspapers, flood reports
  - Paleoflood data
- Snow Data
  - Snow Course, SNOTEL, SNODAS
- Climate Data
  - Projections and models
  - CMIP5 Downscaled archive

Hydrologic Hazard – Extreme Storm data

Hydrologic Hazard Data – Peak Flows
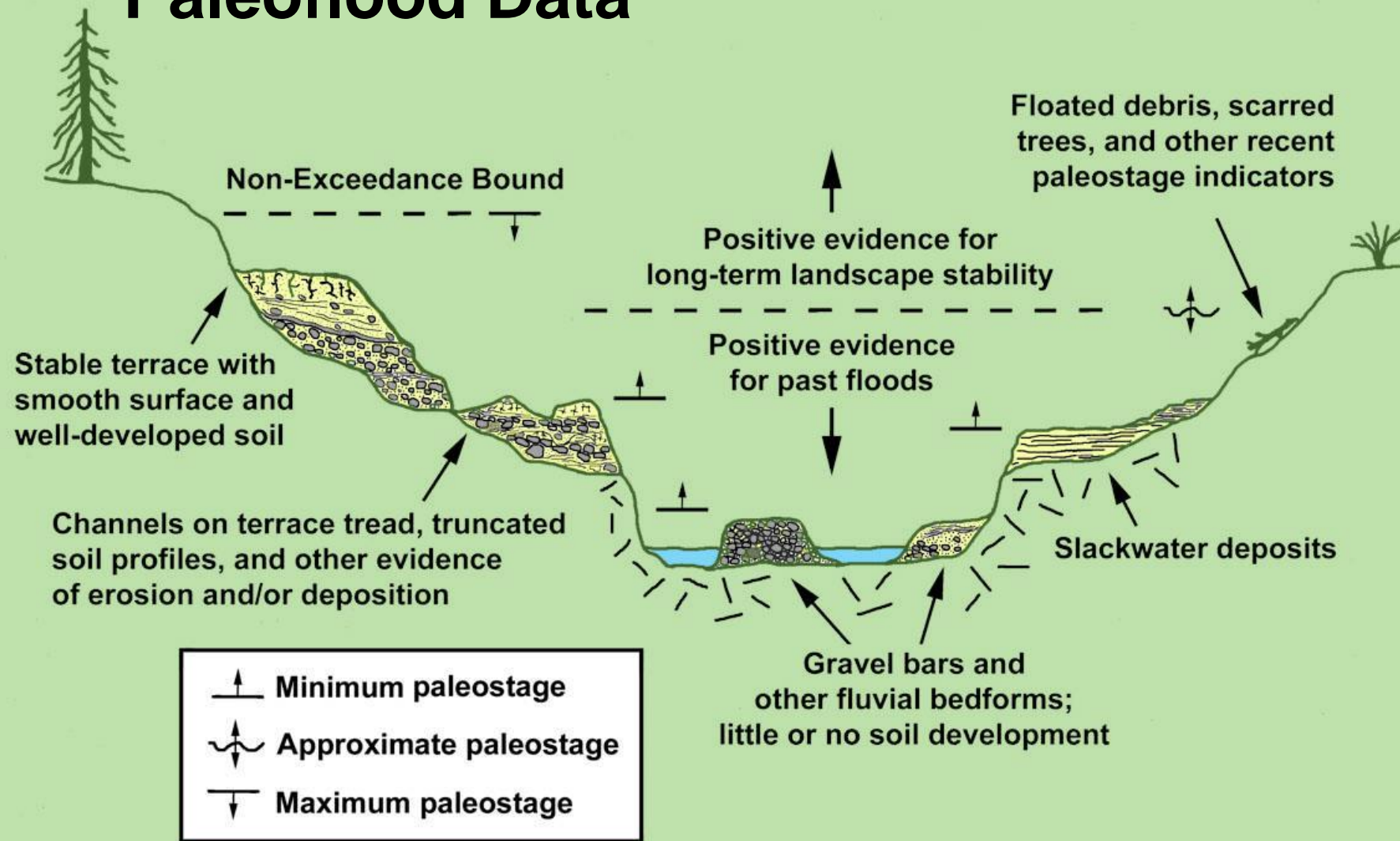

Battle Creek, Shasta County, CA: Dec. 22, 1964

Wind River near Crowheart, WY: Jul. 01, 2011

USGS National Water Information System and flood studies

Paleoflood Data

House et al. (2002) AGU Paleoflood Monograph

Data Acquisition and Evaluation
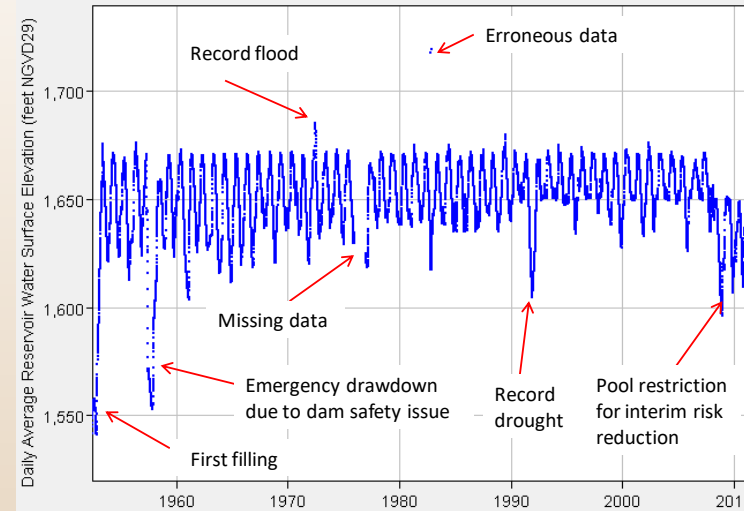
- Understand data source (collection interval, what is being measured)
  - Daily average, peak, something else
  - Recorded (stage) or calculated (computed from observed stage using a rating curve)
- Check for missing data, data shifts, and erroneous data
- Check that data is representative of conditions assumed for the risk analysis

Hydrologic Hazard Methods- Streamflow

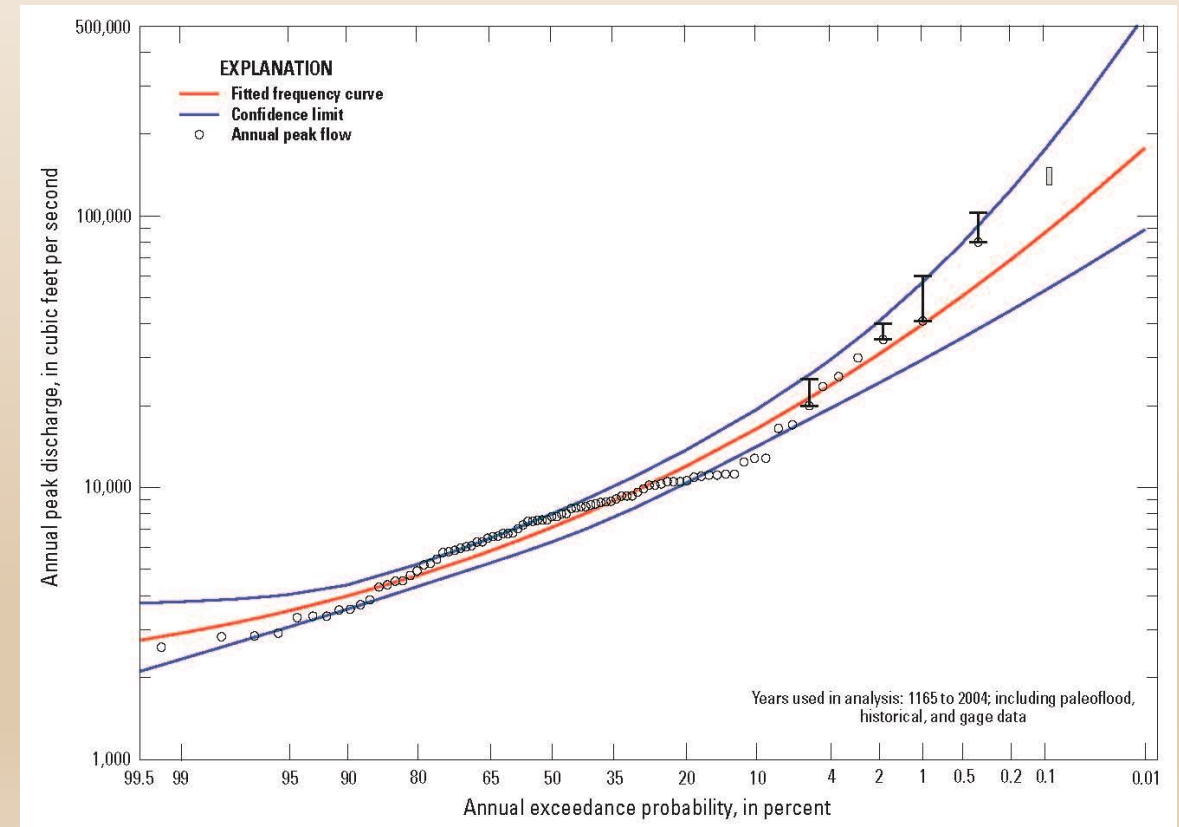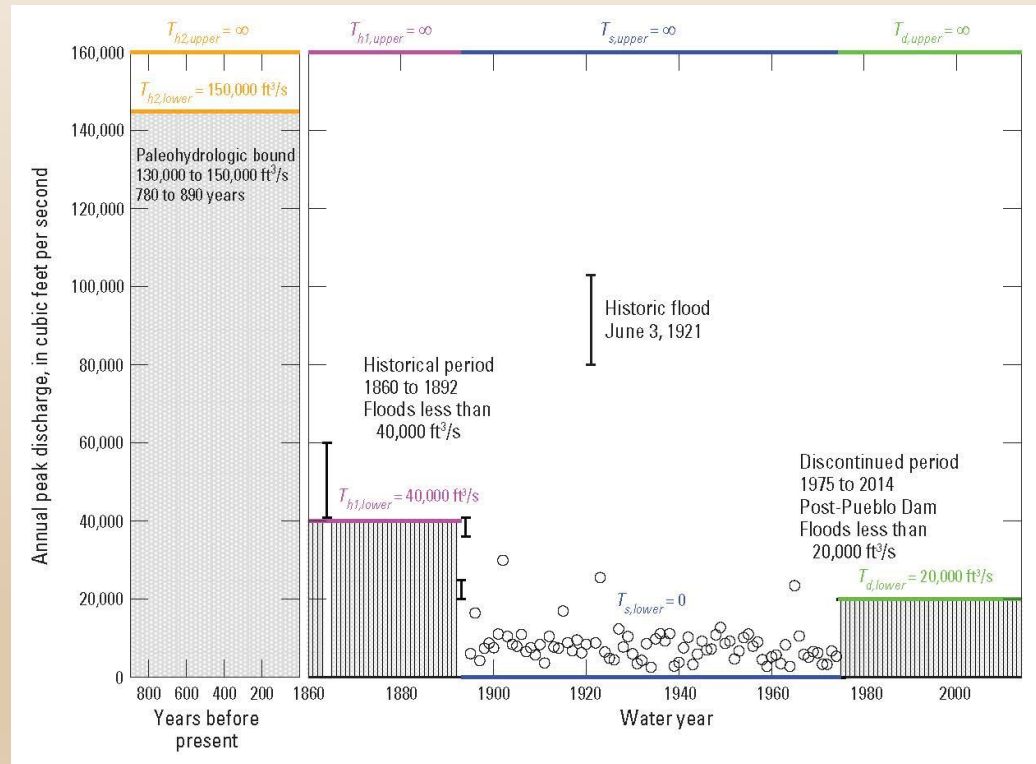| Method (Agency)	Description (reference)	Inputs	Assumptions	Hydrologic Hazard Curve	Why Choose	Level of Effort
Bulletin 17C (EMA-LP-III) USGS PeakFQ; HEC-SSP (USACE, USBR, FERC)	Peak-flow and volume frequency analysis with historical/paleoflood data - EMA (Cohn et al., 1997; England et al., 2018)	Peak flow, historical data, paleoflood data, regional skews	LP-III flood frequency distribution with moments and regional skew	Peak flow frequency and confidence intervals; Volume Frequency	Federal guidelines for flood frequency; uses historical and paleoflood data when available	Low to moderate
FLDFRQ3 (USBR)	Bayesian Peak-flow frequency analysis with historical/paleoflood data - FLDFRQ3 (O'Connell et al., 2002)	Peak flow, detailed paleofloods	Various flood frequency distributions with likelihood	Peak flow frequency and confidence intervals	Detailed paleoflood data available; need FFA confidence intervals, choice of distribution	Low to moderate
Hydrograph Scaling (USACE and USBR)	Balanced Hydrographs and Pattern Scaling (England, 2003, Smith et al., 2018)	Hydrographs and volumes	Hydrographs represent extreme flood response; requires FFA for scaling	Hydrographs and volumes; based on peak flow and volume frequency	Ratios of the IDF hydrograph and statistically based balanced and patterned hydrographs	Low
Reservoir Frequency Analysis (RMC-RFA) (USACE)	Streamflow Volume Stochastic Modeling with reservoir routing (Smith, 2018)	Volume frequency, hydrographs, flood season, initial reservoir stage	Inputs defined by distributions, volume-frequency, observed hydrographs, and pool duration frequency	Reservoir elevation and confidence intervals	Monte-Carlo methods to sample inputs; combine inflows and routing, quantify uncertainty	Low to Moderate
Watershed Analysis Tool (HEC-WAT) (USACE)	Streamflow Volume Stochastic Modeling for Flood Risk Analysis with HEC-ResSim (within HEC-WAT)	Pool duration, volumes, and Hydrographs	Inputs defined by distributions, volume-frequency observed hydrographs, and pool duration frequency	Reservoir elevation and confidence intervals	Monte-Carlo methods to sample inputs; quantify uncertainty; system/downstream effects with coincident frequency	High

Bulletin 17C Streamflow - Example

Arkansas River at Pueblo, CO – record flood (1921), historical and paleoflood data, reservoir records

- 1,000 years of at-site flood information; additional data at 3 upstream sites spanning several thousand years

Hydrologic Hazard Methods: Rainfall-Runoff

Method (Agency)	Description (reference)	Data Inputs	Assumptions	Hydrologic Hazard Curve Product	Why Choose	Level of Effort
Australian Rainfall-Runoff (USBR, FERC)	Australian Rainfall-Runoff Method (*Nathan and Weinmann, 1999*)	PMP design storm; rainfall frequency; watershed parameters	Exceedance Probability of PMP; average watershed parameter values; runoff frequency same as rainfall frequency	Peak flow and hydrographs; based on rainfall frequency and PMP	Similar runoff model as PMP/PMF; familiar design concepts	Moderate to High
SEFM (USBR, FERC)	Stochastic Event-Based Precipitation Runoff Modeling with SEFM (*MGS,2005, MGS, 2009; Schaefer and Barker, 2002*)	Rainfall gages/ detailed regional rainfall frequency, watershed parameters, snowpack, reservoir data	Main inputs defined by distributions; unit hydrograph; rainfall frequency using GEV/L-moments	Peak flow frequency; hydrographs; volume frequency; reservoir elevation frequency	Monte-Carlo methods to sample input distributions	High
HEC-WAT (USACE and USBR)	Watershed analysis tool coupling rainfall-runoff model (HEC-HMS), river routing (RAS), and reservoir operations for system-wide basin flood studies	Can be Regional extreme storm DAD data or meteorlogic extreme storm data, watershed parameters, snowpack	Main inputs defined by distributions; unit hydrograph; rainfall frequency using GEV/L-moments or weather generator	Monte Carlo inputs and resampling; Reservoir elevation (pool) frequency curves, flood volumes, and hydrographs	Flexible framework for system-wide flood modeling with coupled components	High

Hydrologic Hazard Methods
## *Rainfall-Runoff* *after NRC (1988)*

- Construct a space-time extreme *rainfall* model
  - ***rainfall probability distribution biggest factor***
  - *Stochastic Storm Transposition*
  - *Regional Extreme Precipitation Frequency Analysis*
- Generate several large storms from model
- Model "deterministic" rainfall-runoff transformation
- Monte-Carlo Simulation
  - Hazard curves for flood peaks, volumes, reservoir stages and Uncertainty

Rainfall-Runoff Calibration and Weighting

Calibrate model results to observed hydrographs and estimated frequency curves (peak/volume) to determine best model input parameters and distributions
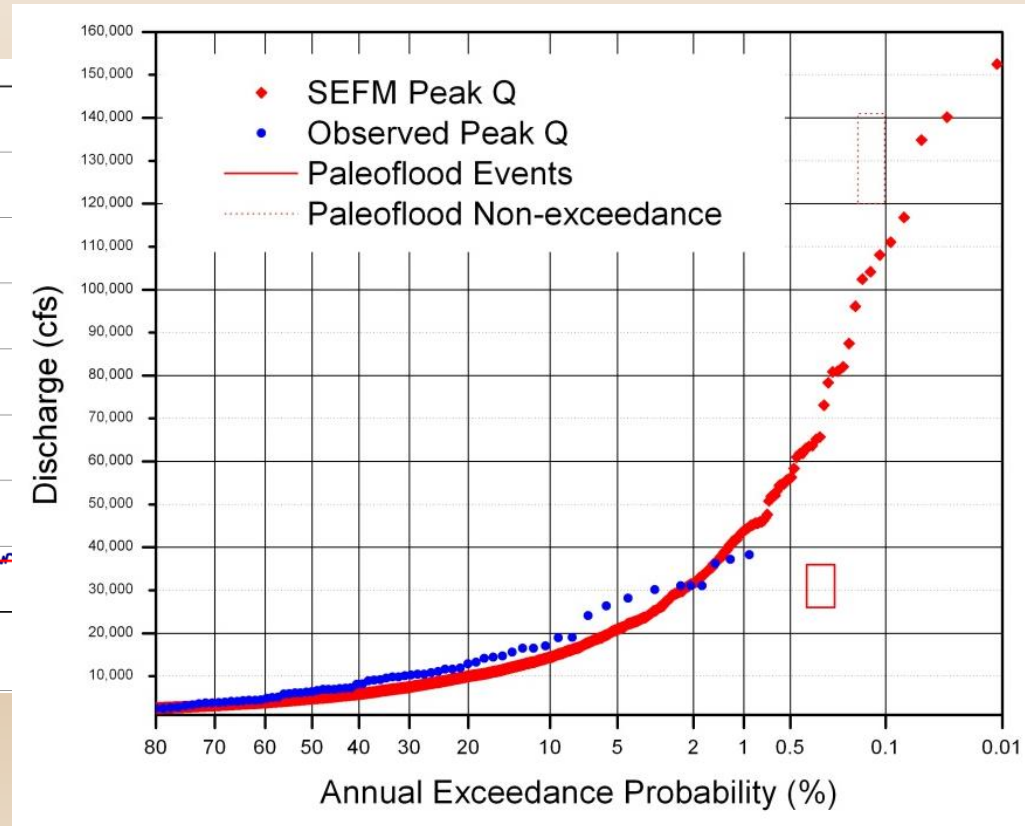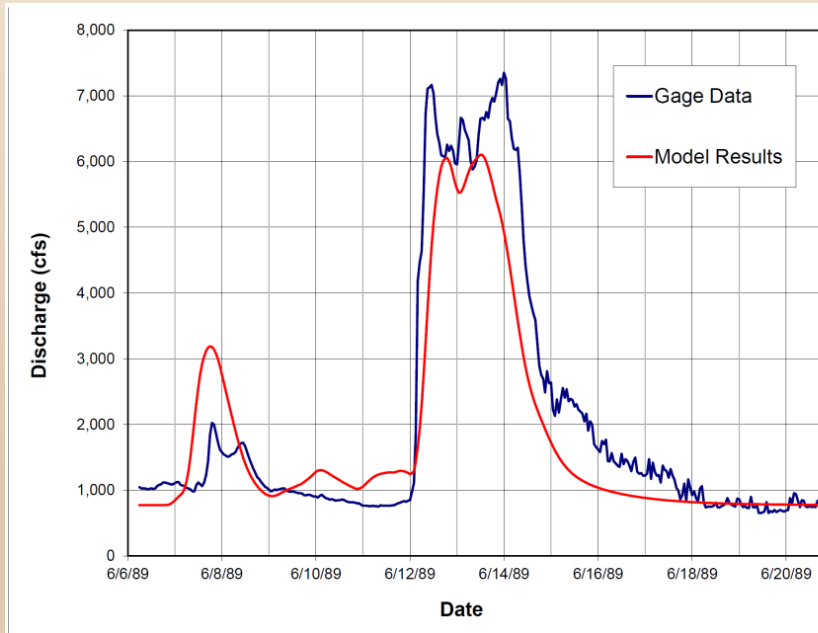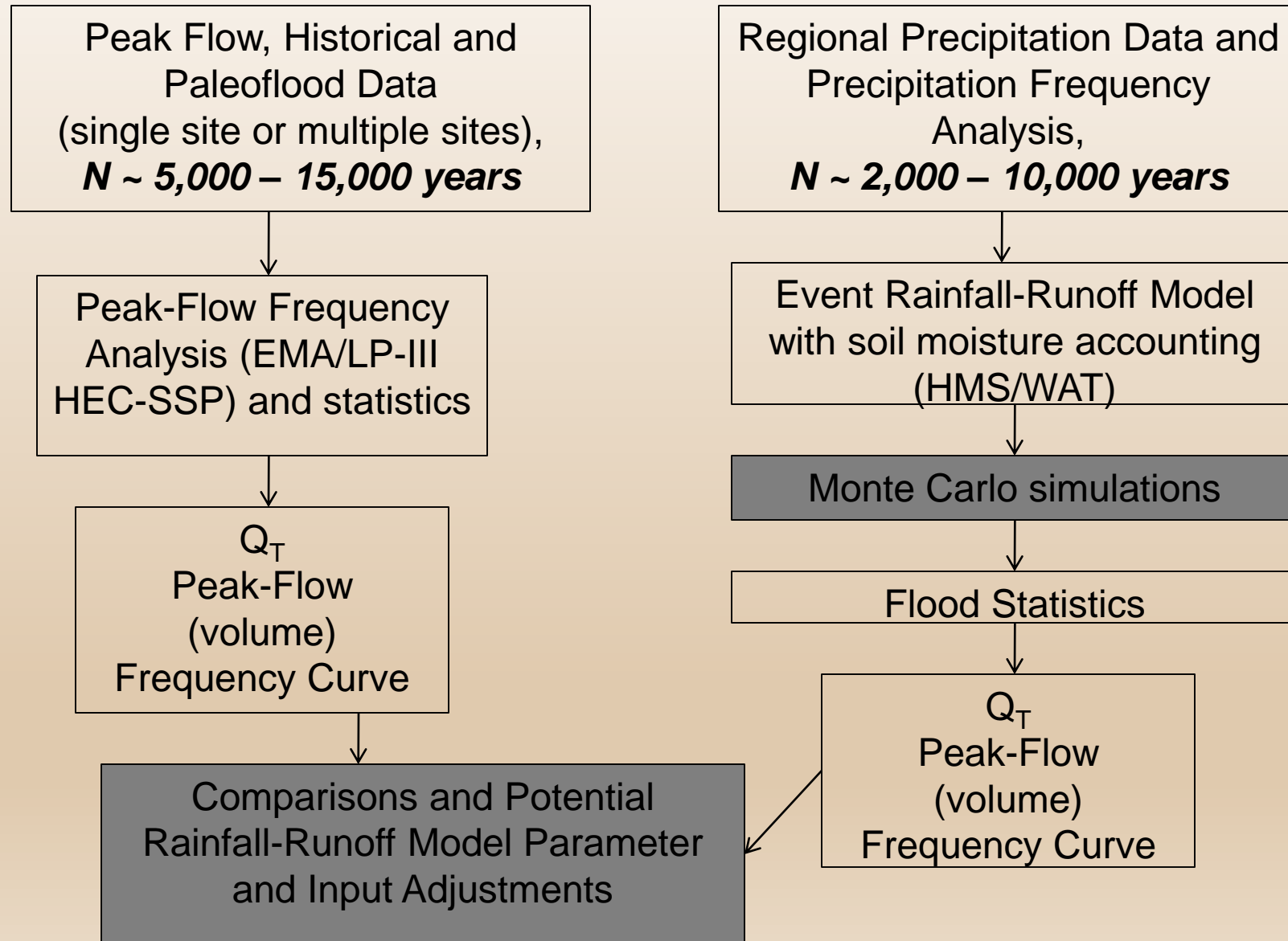
Represent Uncertainty

- Uncertainty of peak flow frequency with paleofloods
- Uncertainty of basin-average rainfall frequency
- Variation in rainfall-runoff parameters and inputs
- Include future Climate projections
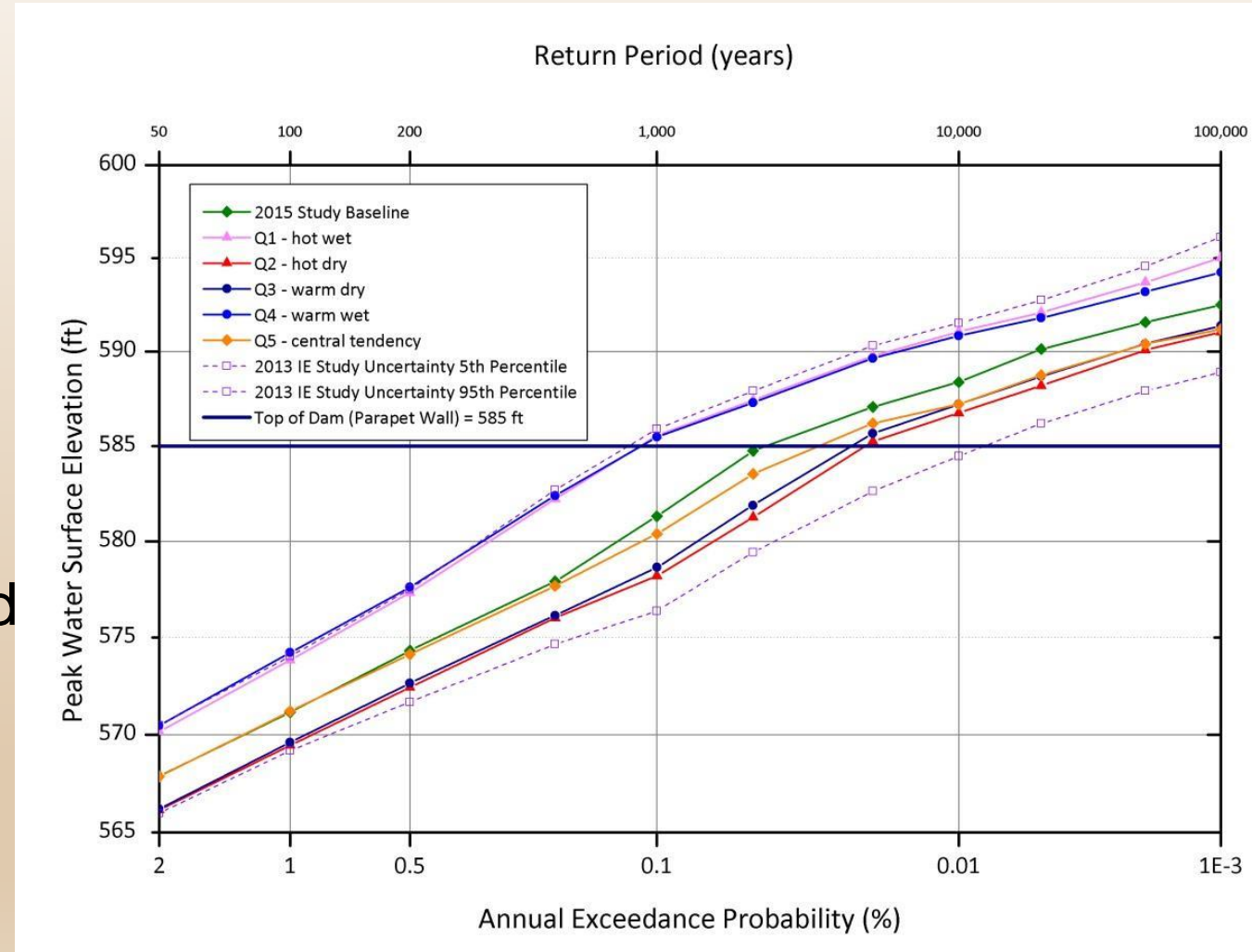
Climate change Pilot for Friant Dam

Hydrologic Hazard
Multiple Methods, Data and Extrapolations

Hydrologic Hazard Methods Scalable Effort

Hydrologic Hazard estimates are typically made for three levels of risk informed decisions. Data and methods depend on type of study:

- Periodic Assessments/Comprehensive Reviews
  - Screening-level/qualitative information used
- Issue Evaluation Studies
  - Increased regional data collection and level of detail
- Corrective Action/Dam Safety Modification Studies
  - Additional at-site data collection and advanced modeling efforts; Monte-Carlo rainfall-runoff modeling; expert elicitation
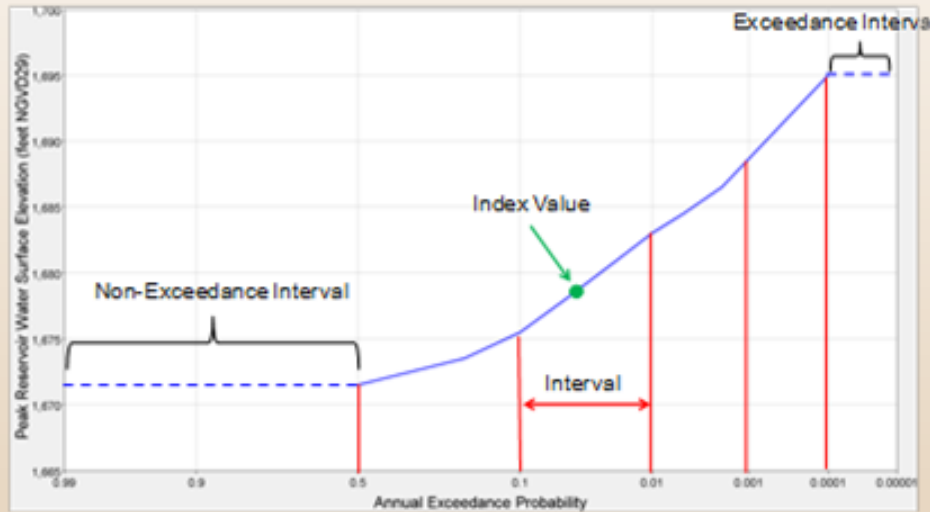
Hydrologic Hazards for Risk Analysis - Inputs
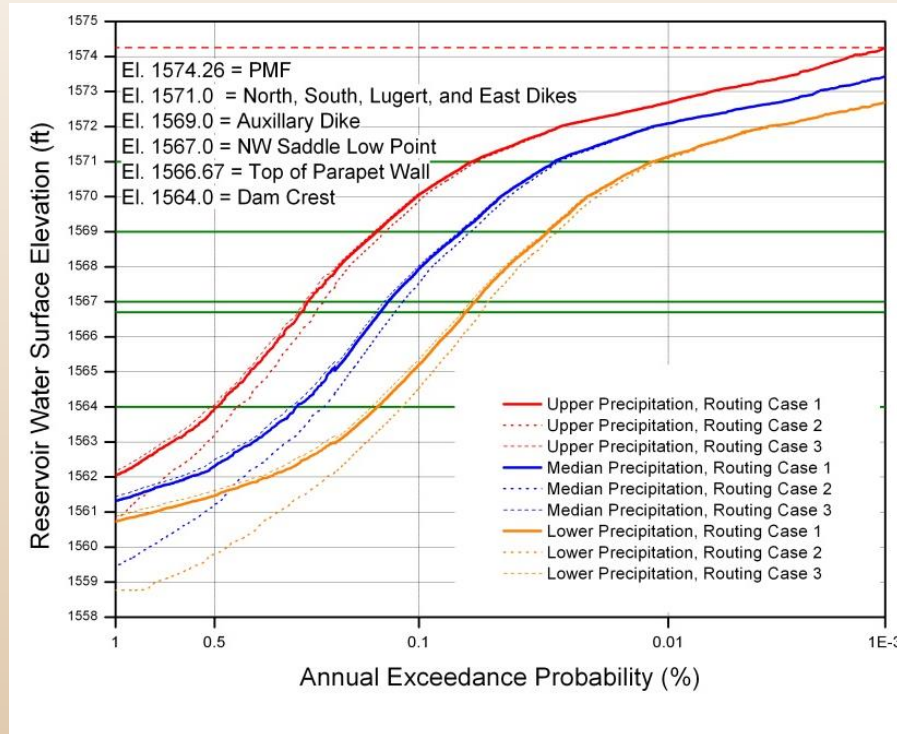
P_l = Probability of Load –
*Hydrologic Hazard Curve
(Reservoir Elevation)*
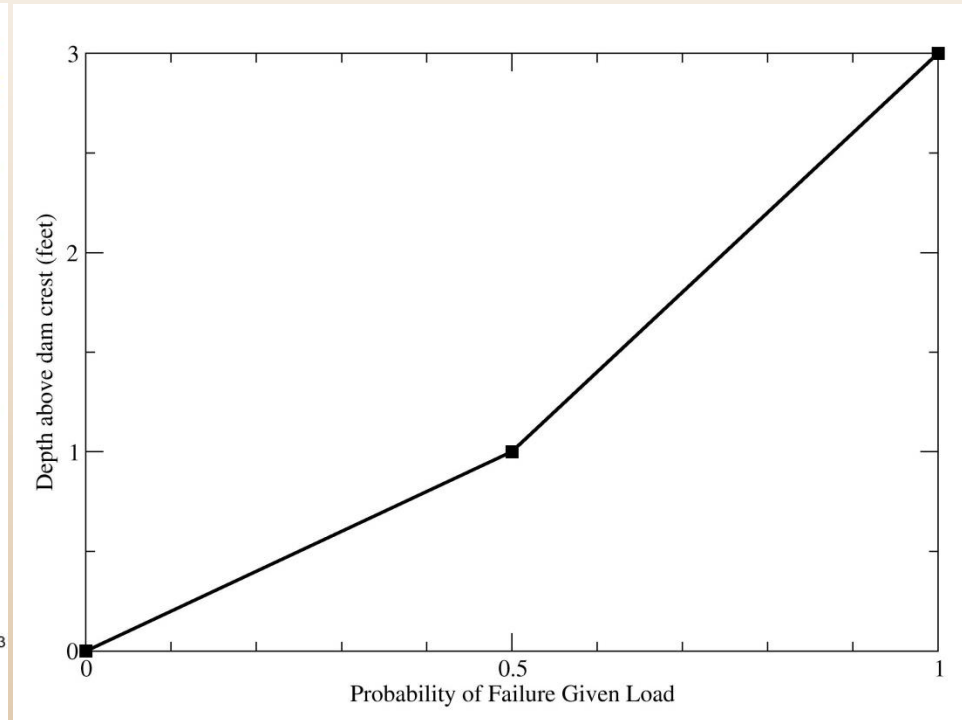
$P_{r|l}$ = Probability of
Response Given Load
(Depth above Dam Crest)

Flood Event Tree Partitions

Elevation			Probability		
Lower Bound	Upper Bound	Index Value	Lower Bound	Upper Bound	Probability
n/a	1671.5	1671.5	1	0.5	0.5
1671.5	1675.5	1673.5	0.5	0.1	0.4
1675.5	1683.0	1679.2	0.1	0.01	0.09
1683.0	1688.0	1685.5	0.01	0.001	0.009
1688.0	1695.0	1691.5	0.001	0.0001	0.0009
1695.0	n/a	1695.0	0.0001	0	0.0001

Questions?

Folsom
Joint Federal
Project
Sacramento,
CA

Reclamation
and USACE
Partnership

New spillway
for improved
flood control